Evaluation of Enhanced Low Dose Rate Sensitivity in Discrete Bipolar Junction Transistors

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35-word Abstract: We evaluate the low dose rate sensitivity in several families of discrete bipolar transistors across device parameter, quality assurance level, and irradiation bias configuration. We discuss the implications of the results for radiation hardness assurance.

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Session Preference: Hardness Assurance (Poster)

I. Introduction

Enhanced-low-dose-rate-sensitivity (ELDRS) has remained a challenge for radiation hardness assurance of linear bipolar integrated circuits (IC). Although ELDRS originates in discrete bipolar junction transistors (BJT), its magnitude is often enhanced in linear ICs [1]. Therefore, while there are qualification standards for linear bipolar circuits (MIL-STD-883G, TEST METHOD 1019.8), there is currently no standard test requirement to screen ELDRS in discrete bipolar transistors [2]. Nevertheless, no study has systematically evaluated the low dose rate response of a wide range of discrete devices of various power levels and switching speeds. Previous studies by Johnston et al. found minimal dose rate dependence for discrete BJTs [1]. In contrast, Nowlin et al. observed low dose rate enhancements of approximately ×2 for highly scaled devices [3]. However the highly scaled devices that showed ELDRS are more similar to the processes in linear ICs, rather than conventional discrete devices. Nonetheless the technology processes and designs of discrete devices have evolved since the early investigations. The changes in various device parameters can significantly impact the low dose rate sensitivity, a phenomenon which we still do not completely understand.

Even with the considerable volume of publications, there still lacks a unified theory that comprehensively explains the physical mechanisms of ELDRS. A widely accepted theory discusses the metastably trapped charges, which helps to create a space-charge effect in the oxide [4]. The space-charge effect slows hole transport, which in turn produces a relatively higher oxide trapped charge density at low dose rate. The space-charge effect will have a great impact for devices with relatively thicker oxides, or in oxides with a relatively higher defect density. Interface traps may play a more important role in determining the low dose rate sensitivity in devices with highly scaled oxides, or in devices with a high density of interfacial dangling bonds. Studies have also shown that hydrogen plays a significant role in interface trap formation [5]–[6]. And the interface trap formation also becomes more enhanced at lower dose rates. The interaction and combination of oxide and interface traps will determine the ELDRS susceptibility of the device.

Recent studies revealed that the magnitude of ELDRS in ICs can continue to increase at dose rates as low as 0.5 mrad(Si)/s, which is a factor of 20 less than the standard test dose rate [7]. The low dose rate enhancement also varies significantly from device to device, such that worst cases show functional failures of the IC. In addition, results presented at the 2011 JEDEC G-12 meeting showed that the gain degradation for 2N2907 devices irradiated at low dose rate (10 mrad(Si)/s) exceeded the manufacturer's specifications at 100 krad(Si) [8].

These findings indicate that the impact of ELDRS may be more significant than previously understood. Since discrete bipolar transistors are used prevalently in space flight systems, it is necessary to assess the ELDRS susceptibility of a large sample size of discrete bipolar devices with various power and speed specifications.

II. Experimental

We include eight different part types from SEMICOA. The devices encompass a wide range of power, speed, and quality assurance level. The devices were placed inside aluminum and lead shielding boxes and irradiated with a 1.1 eV Gamma rays source at ambient temperature. Four to five samples of each part type were irradiated under biased configuration (collector-emitter reverse biased to 80% of maximum rating with base open) and four to five samples were irradiated with terminals grounded, for each dose rate. One to two samples of each part type were used as controls. The devices were characterized using the Keithley 2435 1kW pulse meter and the Keithley 100W source meter.

III. Results and Discussion

Figure 1 shows the average change in the inverse current gains (Δh_{FE}^{-1}) at the lowest operational injection level, as a function of dose for different part types, irradiated unbiased at 10 mrad(Si)/s. The

2N2222, 2N2907, 2N2369 and 2N3700 showed the highest radiation-induced degradation, while the 2N5153 and 2N5154 showed minimal degradation at the lower injection regions. Figure 2 shows the average gain degradation as a function of collector current, for devices irradiated under biase at 10 mrad(Si)/s to 20 krad(Si). We note that the error bars in all the figures indicate part-to-part standard deviation. We observed significant degradation to the current gain at the lower injection regions for the 2N2222, 2N2907, 2N2369, and 2N3700, as is commonly observed in bipolar transistors [9]. However the 2N5153 and 2N5154 showed the largest gain degradation at the higher injection regions, although the degradation levels are comparably lower. The current gain degraded to approximately 50% and 98% after 20 krad(Si), for the 2N2222 and 2N5153, respectively.

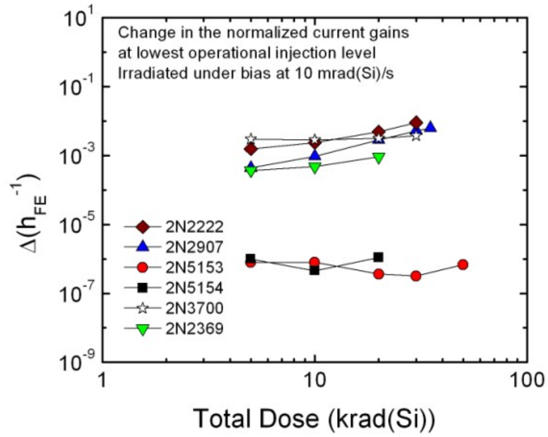

Fig. 1. Change in the inverse current gain (at lowest device operational injection level) as a function of total dose for various part types, irradiated at 10 mrad(Si)/s.

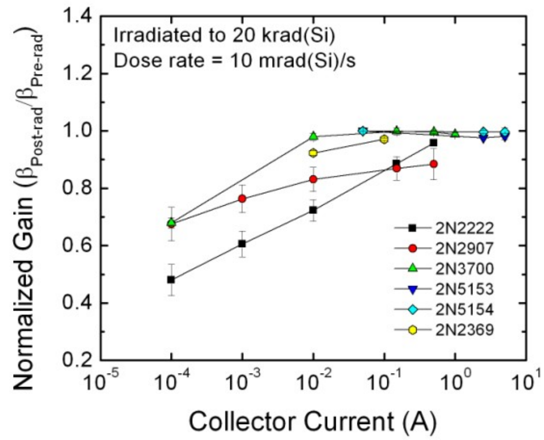

Fig. 2. Normalized current gain ($h_{FE-postrad}/h_{FE-prrerad}$) as a function of collector current for various part types, irradiated to 20 krad(Si) at 10 mrad(Si)/s.

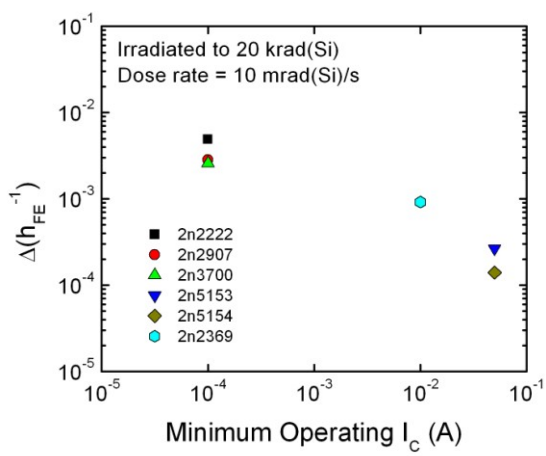

Fig. 3. Change in the inverse current gain for various part types as a function of the minimum device operating collector current ratings, irradiated to 20 krad(Si) at 10 mrad(Si)/s.

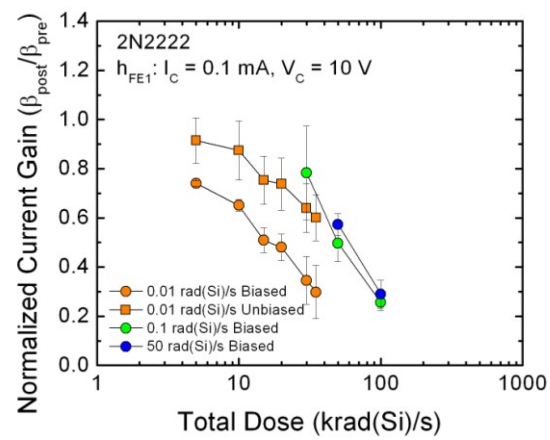

Fig. 4. Normalized current gain as a function of total dose for the 2N2222, irradiated at 10, 100 mrad(Si)/s, and high dose rate under biased and unbiased configurations.

Various factors can influence the total dose response of discrete bipolar transistors. Previous studies have explored the effects of different device parameters on the radiation-induced degradation of discrete BJTs and bipolar linear ICs [1]. For example, the current gain degradation in some devices varied with the collector-emitter breakdown voltage [1]. The devices here did not show similar behavior. We observed that the current gain degradation varied inversely with the minimum device operating current, as shown in Figure 3. The Δh_{FE}^{-1} for devices with the lowest operating currents was approximately 1 order of magnitude higher than for devices with the highest operating currents. The degradation levels also correspond to the device operation range. The three devices with the highest degradation levels also contained the widest range of operating current. Although specific device geometry parameters are not disclosed here, past studies have found that devices with wider operating ranges generally have much larger emitter perimeter to area ratios (P_E/A_E) [3]. The P_E/A_E ratio can affect the radiation-induced degradation, since it relates to the emitter-base depletion region, although Johnston et al. found that the range of the damage factors did not correlate strongly with the P_E/A_E ratio [1]. Nevertheless the device geometry may contribute partly to the degradation dependence observed in Figure 3. On the other hand, the level of low dose rate sensitivity does not correlate strongly with the minimum operating current. While the 2N2222, 2N5153, and 2N2907 exhibited various degrees of low dose rate sensitivity, the 2N2369 and 2N5154 showed no dose rate sensitivity at this stage of the irradiation. Therefore there are other design and/or process parameters that influence the low dose rate response.

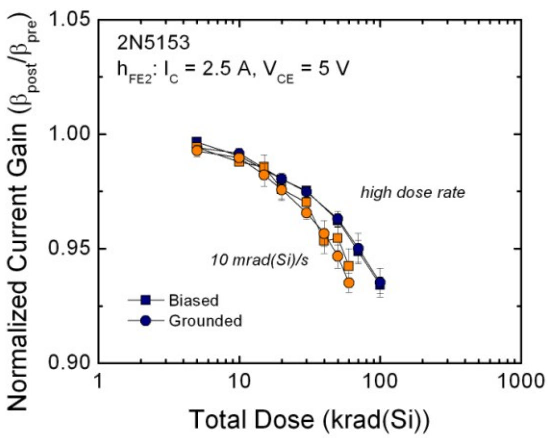

Fig. 5. Normalized current gain as a function of total dose for the 2N5153, irradiated under biased and unbiased configurations, at high dose rate and 10 mrad(Si)/s.

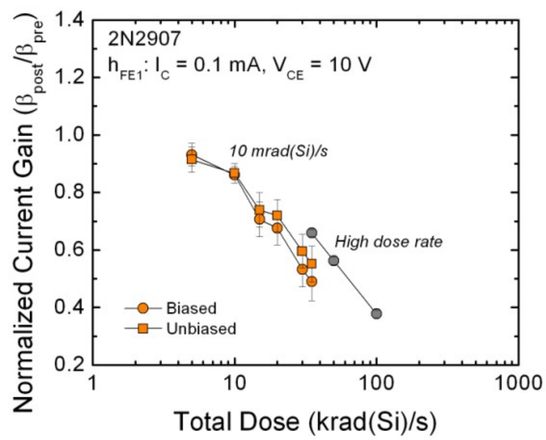

Fig. 6. Normalized current gain as a function of total dose for the 2N2907, irradiated at high dose rate and 10 mrad(Si)/s under biased and unbiased configurations.

We evaluate the low dose rate sensitivity for the 2N2222, 2N5153 and 2N2907, in Figures 4, 5, and 6, respectively. Figure 4 shows the normalized current gain as a function of dose for the 2N2222, irradiated under bias at 10, 100 mrad(Si)/s and at high dose rate. The 100 mrad(Si)/s and high dose rate data are obtained from a previous test from the same wafer lot. The data trend shows enhanced degradation for the devices irradiated at 10 mrad(Si)/s relative to the devices irradiated at 100 mrad(Si)/s and at high dose rate. In fact, the devices irradiated at 10 mrad(Si)/s showed an enhancement of ×4.33 in the Δh_{FE}^{-1} after 30 krad(Si), relative to the devices irradiated at 100 mrad(Si)/s. Figure 4 also shows enhanced degradation for the devices irradiated under bias relative to the devices irradiated unbiased at 10 mrad(Si)/s. The worst case current gain was approximately 50 after 35 krad(Si), which is the minimum specification limit.

We observed slight low dose rate enhancement in the 2N5153. Figure 5 shows the normalized current gain (I_C = 2.5 A) as a function of dose, for the devices irradiated at 10 mrad(Si)/s and at high dose rate. The current gain degradation is relatively minor at this stage of the irradiation. The level of low dose rate sensitivity is also significantly less compared with the 2N2222. Interestingly, the 2N5154 showed slightly reduced degradation relative to the 2N5153. The two device types are almost identical in design, other than the polarity. Typically NPN transistors are more susceptible to ionizing radiation than PNP transistors [1], [3]. We will investigate the phenomenon further in the full paper. There is also minimal bias dependence at low and high dose rate.

Figure 6 shows the normalized current gain as a function of dose for the 2N2907, irradiated under bias at 10 mrad(Si)/s and at high dose rate. The only comparison point is at 35 krad(Si), since the high dose rate data is taken from a previous test on the same wafer lot. Nevertheless, the parts irradiated at low dose rate appear to degrade more significantly relative to the devices irradiated at high dose rate. The Δh_{FE1}^{-1} showed a low dose rate enhancement of ×1.93 after 35 krad(Si). In addition, we observed minimal bias dependence, similar to other part types in the study, other than the 2N2222.

The general lack of bias dependence in these devices suggests that the trapped charges over the emitter-base region likely dominate the damage. However the bias dependence observed in Figure 4 indicates that charge accumulation above the collector-base region also contributes to the gain degradation for the 2N2222. Furthermore, the relatively small radiation-induced increases in the collector-base leakage current reveals that increased recombination current in the base, rather than channel inversion, is primarily responsible for the enhanced degradation in the biased 2N2222 devices. Many linear ICs show ELDRS when irradiated in the unbiased configuration, which has applicability for cold spare parts in satellite systems. Therefore the bias dependence of the radiation-induced degradation at low dose rates is particularly relevant for hardness assurance.

IV. Conclusion

We have presented results of low dose rate total dose irradiation of several families of discrete bipolar transistors. We observed various degrees of low dose rate sensitivity for the 2N2222, 2N2907 and 2N5153, while other devices showed minimal or no dose rate sensitivity. We found that the level of the radiation-induced current gain degradation varied inversely as the minimum device operating current. In addition, the devices exhibited minimal bias dependence, with the exception for the 2N2222, which showed enhanced degradation for the devices irradiated under bias at low dose rate.

In devices where the radiation-induced current gain degradations are significant (i. e. 2N2222 and 2N2907), minor ELDRS enhancement can cause parametric failure prior to 100 krad(Si). Furthermore, since discrete BJTs are currently widely used in satellite systems without low dose rate qualification, the results of this study are pertinent for radiation hardness assurance.

V. References

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